

Combining desiccant dehumidification with Hot Air and Microwave food drying: a sustainable and economical method to produce dried snacks

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Abstract

Solar hot air drying is a food dehydration method that is quickly gaining traction in South Asia due to its very low capital and operational cost. The long drying time and high temperature are the primary sinks of product quality in this process. The deterioration of cosmetic quality of food due to exposure to high temperatures over prolonged durations is an economical challenge as well since it results in a portion of dried product to be discarded. The objective of this work was to reduce the energy consumption and drying time, while obtaining a product quality competitive with energy extensive methods. To achieve this objective, a combined desiccant-convection-radiation dryer was designed and tested. A solar powered thermally regenerated desiccant dehumidifier was installed upstream of a Hot air – Microwave combined food dehydrator. The experimental results were compared with and without desiccant dehumidification. 'Solanum tuberosum' potato was cut into 3 mm thick slices and identical control samples of the potato slices were dehydrated using Hot air drying at 60 °C, Microwave drying at 1 kW Microwave power, Combined Hot air – Microwave drying, and Desiccant assisted Microwave – Convection drying. The drying time of the control sample with Desiccant assisted Hot air – Microwave drying was found to be the lowest, resulting in 81.7% reduction in drying time compared to Hot air Convection drying, 27.7% compared to MW drying and 13.3% compared to Microwave – Convection drying. The color retention was also found to be the highest for Desiccant assisted Microwave – Convection drying. The dried potato slices preserved 87.8% of their original color with this method, which is comparable to the results that are obtained with Freeze Drying.

Introduction & Literature Review

The global population is increasing at an accelerating rate and the global climate is rapidly changing^{1,2}. This creates a massive load on energy and food systems that must meet the requirements of an inflating population². Energy and food systems also happen to be a major strain on the environment, positioning themselves as major hurdles that are offsetting efforts made to curb climate change³. Moreover, 30% of the crops harvested in agricultural regions are lost over their supply cycle⁴. The difference in changing market-supply of food items due to harvest cycles and weather conditions, against the relatively consistent market-demand of certain food items also results in significant losses of food products when the supply exceeds demand. Conversely, prices soar when the supply struggles to meet demand⁵. This creates an urgent need for eco-friendly food preservation processes that are reliable, safe, and fit to make global food systems more secure. Suitable food preservations processes are characterized by their easy adaptability for producers operating in agricultural regions, low energy consumption, short yield times, and competitive product quality.

Post-harvest food losses. It is known that one third of the food that is produced globally is lost over its supply chain⁶. In developing countries, most of this food loss occurs during post-harvest handling⁷. There are multiple factors that contribute to post harvest losses. One of the biggest factors happens to be the high perishability of food items⁸. Producers attempt to preserve their food items and increase their shelf

life, or add value to them, by processing them into dried snacks. However, most affordable food processing methods fail to preserve most of the crops to an acceptable degree of quality⁹. While there are industrial-scale food processing systems available in developing countries, they are energy intensive and cannot be procured and operated by small and medium scale producers due to their high capital and operational costs¹⁰. Energy inefficiency of drying methods that deliver product with competitive quality makes them unsustainable and therefore unfit to meet sustainability goals in the future. Post-harvest losses are also linked to nutrient deficiencies in developing regions¹¹. For these reasons, reducing post-harvest food loss and increasing shelf life of food items is vital to make the world's food systems more secure and immune to climate change and the increasing demands that come with population expansion.

Climate Change. The global population is expected to reach 10 Billion by 2050¹². This will be followed by higher overall consumption of food and energy. Global food production will have to increase by 60% to meet the demands of future population¹³. The strain incurred on food systems is therefore expected to increase the overall Carbon emissions of food production and processing^{3,14}. Food systems are already responsible for 34% of total GHG emissions, releasing 18 equivalent Giga-Tons of CO₂ annually¹⁵. Given that most technologies that preserve food without deteriorating quality are energy expensive, food preservation and storage is expected to strain energy harvesting and storage systems as well¹⁷. Reduction in post-harvest losses, therefore, is not only related to economic safety of farmers and countries reliant on agriculture, but also to the environmental safety of a warming planet¹⁸.

Food dehydration. Going as far back as 1490 BC, drying is one of the oldest methods of preserving food items. In modern times, it is still one of the most popular methods of food preservation¹⁹. While most of the world dries its food by simply leaving it out in the sun with some sort of porous or transparent covering to keep the pests away²⁰, the dried food products that meet consumers' nutritional and cosmetic criteria to pass as 'snacks' are produced with energy inefficient processes like Freeze Drying, Osmotic Dehydration or Vacuum Drying²¹. 25% of the total energy spent on food processing goes solely into drying²². The data indicates that while drying of food items is one of the most important and scalable methods to preserve food, it also has a massive impact on the climate²². Thus, it is imperative that the academia and industry working in food preservation focus on drying methods that are low-cost, eco-friendly and produce quality product that incentivizes small and medium scale producers with high profit margins and low operational cost.

Methods of dehydration. As stated, the most popular method of food dehydration is Open Sun Drying. The primary attraction with this method is that it requires little to no capital and operational cost and can be used to dry large quantities of food. However, its primary drawback is that it can often take several days to produce a feed of dried food. During this time, the food is left vulnerable to changing weathers, fluctuating humidity levels and pests⁹. The long drying times also result in almost complete deterioration

of nutrient content present in food and damage the color and shape of food items due to high levels of shrinkage and oxidation^{23,24}.

Another common method of dehydrating food items is Convective Drying. Like Open Sun Drying, Convective Drying works by heating up the surface of a food item. Since the surface of the food item is saturated with moisture, the layer of air surrounding the surface becomes both hot and humid and thereby high in vapor pressure. This causes the water present on the surface to evaporate into surrounding air²⁵. The surface also conducts heat energy into inner layers of food item, causing moisture to migrate from inner layers towards the surface where it is evaporated²⁶. Convective Drying is often conducted with gas fired ovens to dehydrate snacks. But in many parts of the world, natural and forced convection with solar flat plate collectors is becoming more and more common to dehydrate food products²⁷. This is called Green House Drying (GHD). The reason GHD is becoming popular is that the cost of a small green house or solar thermal collector is quite low and the system that is produced can dehydrate food items within a single day, significantly cutting down the drying time incurred with Open Sun Drying²⁸. Compared to Open Sun Drying, Convective Drying has been found to drop the drying time of figs by 38%²⁹, cherry tomatoes by 74%³⁰, green chilli by 53%³¹ and cassumunar ginger by 67%²⁸. Due to most of the energy used in this process coming from solar thermal sources, Solar Convective Drying is a very low emissions drying method. The problem with it, however, is that product quality is not up to mark for international market standards. Exposure to high temperatures over prolonged durations deteriorates the color of food items. While the end quality of food obtained with Convective Drying is still better than Open Sun Drying, it is not on par with high energy and eco-hazardous methods like Freeze Drying³².

Also called Lyophilization, Freeze Drying is the leading drying method used to produce dried berries and snacks retailed on international shelves³³. This method of food dehydration works very differently from techniques that evaporate moisture via heating. Instead of heating the moisture in food from liquid to vapor (gas), Freeze Drying freezes it into solid ice crystals and then quickly turns the solid ice into vapor directly when temperature is elevated, via sublimation³⁴. The water vapor is extracted by a vacuum pump. The mechanism of moisture removal in Freeze Drying is sublimation, as opposed to evaporation³⁵. Since food is mainly damaged by exposure to high temperatures in other methods and Freeze Drying operates at low temperatures, it is characterized by high nutrient, color, and shape retention³³. This makes Freeze Drying fit to dehydrate foods that are vulnerable to thermal damage³⁶. Since the process involves limited air contact and flow, Freeze Drying is also fit for drying foods like apples and bananas that are highly vulnerable to oxidation damage³⁷. For these reasons, Freeze Drying is often used as a metric to test the quality of food items dried with other methods³². But the problems with Freeze Drying are its long drying times and high energy consumption.

Freeze Drying consumes 58% higher energy compared to electric resistance Convective Drying and 500% higher energy compared to Microwave – Convection Drying¹⁰. It is also found to consume 180% or 1.8 times more time to dry fruit compared to Convective Drying and 1728% or 17.3 times more time

compared to Microwave assisted Convective Drying¹⁰. Owing to these reasons, Freeze Drying is a highly eco-hazardous drying method and due to the capital cost of equipment and operational cost of energy, it is not fit for small and medium scale producers in developing countries to use Freeze Drying.

Radiation Drying is conducted using Ultrasonic, Infra-Red or Microwave radiations. Radiative methods work by exciting the moisture present within all of the food item rather than just the surface¹⁷. This results in very short drying times, and fast drying rates³⁸. Volumetric heating of food, as opposed to surface heating, also reduces shrinkage and nutrient deterioration since the dry mass of the food item does not undergo extreme thermal stress³⁹. Out of the three common types of penetrative radiations, Microwave radiation results in the most uniform heating and nutrient retention⁴⁰. Compared to Convective Drying, Microwave Drying has been found to drop the drying time of apple by 55%⁴¹ and button mushroom by 90%²⁵. It has also been found that MWD at lower temperatures preserves cosmetic value and prevents food from undergoing high levels of oxidation and scorching⁴².

While MWD is a reasonable balance between product quality, drying time and energy efficiency, the quality of product is still not comparable with Freeze Drying¹⁰. Therefore, Microwave Drying is preferably combined with other methods⁴³. Combined methods tend to overcome the limitations of individual methods and enhance their benefits. One of the most common hybrid or combined food drying methods in literature is Microwave – Convection Drying. Microwaving a food item while blowing hot air over it results in heating of the bulk food compound without allowing the surface temperature to rise to undesirable levels⁴⁴. This is because the surface temperature is maintained close to the temperature of hot air which is facilitating a higher rate of evaporation as well. This control over surface temperature reduces scorching of food surface, results in better nutrient and color retention and reduces the total drying time compared to each of the individual methods⁴⁵. It has been reported that compared to other hybrid methods like MWD+CD+US, CD+USD and CD alone, CD+MWD consumes lower specific energy i.e., energy consumed to remove 1 kg of water from a food item⁴⁶. It has also been reported in literature that while MWD and CD on their own result in high levels of shrinkage of food item, combining them significantly reduces volumetric shrinkage⁴⁷. Microwave – Convection Drying is characterized with 50% reduction in both drying time and specific energy consumption compared to CD on its own⁴¹. For foods with high moisture content and very porous, pulpy structures like lemons and oranges, MWD+CD tends to drop the drying time by as much as 97% compared to CD⁴⁸.

However, Microwave – Convection Drying still does not retain cosmetic quality to the same degree that Freeze Drying does. The reason being that Microwave – Convection Drying still causes thermal damage to the food surface⁴⁹. Scorching is a consequence of high surface temperature which is needed for high rates of moisture evaporation. High temperatures are needed for drying because rate of moisture evaporation depends on vapor pressure difference between the layer of air sticking to the food surface, and the many layers of air surrounding the food surface as shown in Figure 3. However, increasing the temperature of air surrounding the surface is not the only way of increasing this vapor pressure

difference. The vapor pressure of the surrounding hot air can be reduced by dehumidifying it⁵⁰. This results in the same or higher vapor pressure difference than that obtained with only Convection or Microwave heating, and unlike heating methods. Achieving a higher vapor pressure difference by using dehumidification does impart any thermal damage to the food surface^{51,52}. Therefore, dropping the humidity of the air used for convection in Microwave – Convection Drying process can result in an equivalent drying rate and drying time without having to increase the surface temperature⁵³. And since the temperature would not be elevated to high levels, dehumidification is supposed to deliver higher nutrient, color and shape retention compared to Microwave – Convection Drying process⁵². Some research studies in literature have demonstrated that conducting CD in the presence of a desiccant material can increase the drying rate or conversely, reduce temperature needed against a fixed drying rate^{50,52,53}.

In this research work, desiccant dehumidification was combined with Microwave – Convection drying. It was theorized that Microwave radiation would create a high rate of moisture migration from inner layers towards the surface; and the dehumidified air surrounding the surface would be able to help evaporate this moisture at lower temperatures, while cooling the surface due to evaporation. This is supposed to be especially helpful towards the end of the drying process when the surface is relatively more moisture depleted and therefore more vulnerable against high temperatures. Moreover, since desiccant dehumidification can be primarily powered by solar heat, the resultant process was low-emission, eco-sustainable and cheaper to operate. This is particularly helpful as reducing food loss, improving product quality and cutting down energy consumption are primary criteria to make drying of food a more sustainable method of attaining food security for the changing planet and population⁵⁴. Color retention of the final product was considered to be the primary criteria for assessment of quality. This is because this research work was targeted on improving the cosmetic quality of food and converting agricultural produce into profitable fast-moving snacks. Cosmetic quality is a major criterion when assessing snacks⁵⁵.

Methodology. Solar evacuated tube collectors were used as the heat source for both convection and desiccant regeneration. Convective food drying is a low-grade energy process that can operate at temperatures below 100 °C, and the desiccant material used, CaCl₂, can also be regenerated at temperatures below 100 °C. The evacuated tube thermal collectors provide sufficient heat input and temperature to regenerate the desiccant material to high concentrations, and to heat the air used for Convective Drying to the temperatures required for this study. To maximize energy efficiency, the desiccant material was selected on the basis of regeneration temperature and the degree of dehumidification required. The desiccant material selected was Calcium Chloride (CaCl₂) due to its high levels of dehumidification and lower regeneration temperatures compared to solid desiccants like Silica or Zeolite.

As shown in Figure 5, A concentrated or 'strong' CaCl₂ aqueous solution was sprayed in the dehumidifier where it removed moisture from air and dropped its RH to low values (~15 %) The CaCl₂ solution was

diluted and slightly heated in the dehumidification process. The air was heated in this process as well due to the heat of vaporization being released as moisture converted from vapor to liquid. The heat is added to both the CaCl_2 solution and the dehumidified air. The diluted solution was heated indirectly with an evacuated tube heater and the heated solution was sprayed to remove moisture from it, regenerating and concentrating the CaCl_2 solution. The concentrated solution was brought back to ambient temperature to be used again for dehumidification. This was done because at lower temperatures, CaCl_2 solution is able to provide higher levels of dehumidification.

The dehumidified air was pumped by a centrifugal fan the speed of which was controlled with PWM signal. Downstream of the fan, a fin-tube type Aluminum heat exchanger was attached. The hot distilled water from evacuated tubes passed through the heat exchanger tubes and heated up the dehumidified air before it entered a Microwave oven that was modified to allow air inlet and outlet. The Relative Humidity of the air dropped even further as it was sensibly heated with the Aluminum Heat exchanger. Inside the MW oven, a Stainless-Steel grill was placed on which 3 mm thick potato slices were scattered. The potato slices were blanched in hot water at 70 °C for 30 minutes and were cooled for 5 minutes prior to the start of drying experiments. Inlet and outlet air's temperature and RH, and food items' mass and surface temperatures were measured at 30 second intervals during the drying process. Each sample that was tested was kept at a starting mass of 35.5 g. Diameters of potato slices were varied to keep the mass of each sample for different experiments the same. The experiments were continued until the mass of the food item dropped from 80% water activity, down to 3% water activity, which corresponds to 7 g of mass containing 6 g of dry potato mass and 1 g of water.

The complete configuration of the drying process is illustrated in Figure 5 and the process is shown on a psychrometric chart in Figure 4. Process 1-2 represents desiccant dehumidification. Due to the heat generated in the conversion of vapor to liquid, the air temperature increases. The process is isenthalpic because the loss of latent heat (dehumidification) is equal to the gain in sensible heat (heating). Following the dehumidification process, process 2-3 represents sensible heating with Aluminum heat exchanger containing hot distilled water from solar thermal collector. This process also causes the RH to drop even lower. Finally, process 3-4 demonstrates food dehydration. As the moisture from the food changes from liquid to vapor and enters into air, it not only humidifies air, but it also cools it. Microwave radiation reduces the rate of cooling. The process 3-4 is inverse of process 1-2 as apparent from the parallel lines. This is because process 1-2 is isenthalpic dehumidification and process 3-4 is isenthalpic humidification or evaporation. Finally, air is exhausted after process 3-4.

Equipment. The weighing machine used to weigh the potato slices was calibrated against lab-weights. The machine had a least count of ± 0.1 g. The air speed of the fan was measured via a hot wire anemometer that was calibrated by the manufacturer. The anemometer had a least count of ± 1 m/s. Its calibration was also tested and validated against other hot-wire anemometers in the lab. The Infra-red thermometer used to measure surface temperatures was calibrated against phase changing water at 0 °C and 100 °C and could measure temperatures at a least count of ± 0.1 °C but had an error to the grade of

±1 °C. The temperature and humidity at inlet and outlet of the oven were measured via a combined thermometer-hygrometer module that was calibrated against WBT, DPT and DBT of air, as well as a lab-grade hygrometer. The thermometer module had a least count of ±1 °C for temperature measurement and ±1% for RH measurement. However, the error and reading fluctuation for the air temperature and humidity module was found to be ±2 °C and ±3% RH.

A 200 Liter, 20 tube evacuated tube solar thermal collector was used as the primary heat source. Based on a power rating of 100 Watts per tube, the power rating of the thermal collector was considered to be 2000 Watts. The piping from the thermal collector was made of PPRC material and was not further insulated against the environment. Two 50 W diaphragm pumps were used to pump the hot distilled water flowing through two heating loops attached with the tank of the hot water heater. The heating loops were used to heat diluted CaCl₂ solution and the dehumidified air, as explained earlier.

The CaCl₂ salt was commercial grade and had 6% impurities as provided by the supplier. The CaCl₂ solution was pumped by 20 W submersible centrifugal pumps for dehumidification and regeneration. In the desiccant regeneration chamber, an axial fan was used for air flow and the desiccant material was pumped into honeycomb structured wetting material made of Cellulose paper.

Table 1 | Key parameters obtained in the experiments that were conducted in this study

Experiment	Process	Drying Time (min)	Energy Consumption (kJ/g)	Color Retention (%)
1	Constant temperature Convective Drying at 60 °C	35.5	10.3	41.2
2	Microwave Drying	9	19	52.2
3	Microwave-Convection Drying at 60 °C	7.5	18	71.6
4	Desiccant assisted Microwave-Convection Drying at 60 °C	6.5	17.1	87.8

Results

Drying time. It was found that Convective Drying at the constant temperature of 60 °C delivered the longest drying time at 35.5 minutes to drying the slices from 35.5 g down to 7 g. When the process was replaced with Microwave Drying, the drying time was reduced by 26.5 minutes or 74.6% compared to Convective Drying. It should follow that combining the two processes should deliver the mean or average of the two drying times, but when tested, it was found that the drying time of the combined Microwave – Convection drying method was lower than either of the two individual methods. The combined method delivered 78.9% lower drying time compared to Convective Drying and 20% lower drying time compared to Microwave Drying. Finally, when the combined method was assisted by

desiccant dehumidification, the drying time was reduced even further. Compared to the Microwave-Convection drying, desiccant assisted Microwave-Convection resulted in a 13.3% reduction in drying time.

Drying rate. As shown in Figure 6, the drying rate for most processes undergoes an exponential decay. In all of the processes, the drying rate tends to stagnate as the slope of the curve approaches zero towards the very end of the drying process. It must be noted that Convective Drying at 60 °C results in the most inconsistent and most rapidly reducing drying rate. It starts fast but quickly decays to very low values. On the other hand, Microwave Drying delivers the most consistent drying rate. The drying curve almost appears to be a straight line that stagnates only when the mass of the sample is very close to 7 g. When Microwave Drying is combined with Convective drying, the drying curve becomes inconsistent compared to Microwave Drying. The drying curve for the combined method appears to dehydrate the potato slices at a very fast rate in the beginning and even when the drying rate drops, it is still higher than that obtained with Microwave Drying or Convective Drying individually. Finally, when the process is assisted with desiccant dehumidification, the drying rate appears to be slightly faster than that obtained without dehumidification for the first 140 seconds. Following that, the drying rate does not drop as significantly as it does for other methods and only shows a sudden decrease when the mass reaches 7.9 g.

Surface temperature. As shown in Figure 7, the surface temperatures for all process rise exponentially. The temperatures start at higher values than ambient conditions and tend to be stagnant and close to the initial value for some time before the rate of temperature increase starts rising exponentially. The surface temperature of the potato slices observes the most linear and consistent increase for Convective Drying at 60 °C. For a very short duration towards the very end of the drying process, the temperature stagnates as the surface temperature approaches the hot air temperature of 60 °C. The surface temperature rise is much more sudden at 330 seconds for Microwave Drying and rises to much higher values compared to Convective Drying towards the end of the drying process. When combined, the surface temperature for the Microwave – Convective Drying process follows a very typical exponential growth curve. Desiccant dehumidification of hot air used in the combined method demonstrates an interesting finding. The starting temperature of the surface is much lower than any of the other methods. This is the only experiment for which the starting temperature was found to be lower than the ambient temperature despite the air being heated up. The temperature rise follows a typical exponential growth curve, but the product reaches 7 g of final mass or 3% w/w moisture activity at a much lower final surface temperature compared to any other experiment involving Microwave radiation. Overall, desiccant use appears to massively reduce the duration for which the surface is exposed to damaging temperatures above 50 °C by 60% compared to the Microwave – Convection drying conducted without desiccant dehumidification.

Moisture Ratio. Typically, the moisture ratio for raw potatoes is 80% w/w water per total mass⁵⁶. The goal was to bring it down to 3% which is a moisture ratio on which bacterial and fungal activity is significantly halted⁵⁷. For 35.5 g samples, this corresponds to a final mass of 7 g. All of the experiments were able to drop the moisture ratio to 7 g as observed in the drying rate curve and the data points. It can be observed

that at higher Moisture Ratios, the difference between drying time among the experiments is much shorter.

Color Retention. The amount of color that is retained by the food product during the drying process was selected as the primary measure of product quality. It was found that the potato slices underwent high levels of scorching and oxidation for Convective Drying at 60 °C. The potato slices were found to have lost 58.8% of their color during drying and the resultant product was highly darkened and browned. Microwave drying delivered an improvement over the Convective method by preserving 11% more color in comparison. Combining the two processes preserved more color than either of the two individual methods. It was able to preserve 71.6% of the original color. However, when the combined method was assisted by desiccant dehumidification, the highest level of color retention was obtained. The product was found to preserve 87.8% of its original color and the dried potato slices had very little browning over the drying process. Use of desiccant dehumidification preserved 46.6% more color compared to Convective Drying, 35.6% more color compared to Microwave drying and 16.2% more color compared to combined Microwave-Convection drying.

Discussion

Drying Time. It can be observed that Microwave drying delivers a 74.6% shorter drying time compared to Convective Drying. This is because Microwave radiation penetrates the food item and heats it up volumetrically. This contrasts with Convective Drying in which the inner layers of the food item are heated up by conduction through the dry mass and water content present in the potato slices. The rate of heat absorption at the surface of the potato slices and the rate of heat conduction from the surface of the potato slices towards the inner layers bottlenecks the drying rate in Convective Drying. As a result, the process takes much longer to dehydrate the same sample compared to Microwave drying. Combining the two processes shortens the drying time even further. This is attributed to the moisture that is migrated to the surface being quickly evaporated due to forced convection, leaving a higher difference in moisture concentration between the surface and the inner layers of the potato slices which in turn increases the rate of moisture migration. But the increase in drying rate is also attributed to the forced convection being able to carry away the moisture at a much faster rate. While Microwave radiation does increase the migration of moisture from inner layers towards the surface⁵⁸, combining the process with Convective Drying increases the mass transfer occurring at the surface. Finally, use of desiccant material drops the drying time even further by 13.3%. This is attributed to the increased vapor pressure difference which increases the drying rate by causing more moisture to evaporate from the surface. The hot air blown over the surface of potato slices in case of desiccant assisted Microwave – Convection process is able to absorb more moisture from the surface for the same flow rate. This increases the overall drying rate and subsequently reduces the overall drying time.

Drying rate. The reason for exponential reduction in drying time is mainly that the resistance to moisture removal increases as the drying process continues. This is because the surface of the food item is fully wetted or saturated with water in the beginning of the drying process⁵⁹. The moisture at the surface can

easily evaporate and thus the drying rate is very fast in the beginning. However, as the moisture at the surface evaporates, the drying rate drops. This is because the moisture that is now removed is located in the inner layers of the food item. This moisture needs to migrate towards the surface to be evaporated; and the migration of moisture is driven by heat. As the drying process continues, the layers of food item that are closest to the surface are dried up more and more and the moisture that remains to be evaporated is located deeper and deeper in the inner layers of the food slices. This is why thinner slices of food items are reported to dry much faster at a more consistent drying rate⁶⁰. For Convective Drying, the drying rate slowly changes and drops down to very low values. Towards the end of the experiment, the drying rate is almost constant at a very low value. This is because the vapor pressure difference provided by the hot air is insufficient to drive the remaining 1 g of water present in the food at a noticeable rate of removal. Microwave drying demonstrates the most consistent drying rate of all the experiments conducted. This is because volumetric heating with Microwave radiation is the only mode of heating in this experiment. All of the moisture present within the food item is excited at the same time. While the moisture at the surface evaporates, the moisture present in inner layers of the food item migrates towards the surface. Since the migration of moisture to the surface almost matches the rate of evaporation from the surface, the rate of dehydration is almost constant, and the drying curve almost appears to be a straight line. Even so, it is not a straight line. It can be seen that the drying rate is not completely linear. The small reduction in drying rate over time is because over time, the moisture that needs to be evaporated is located further and further away from the surface and takes more time to migrate towards the surface. When the mass of the slices reaches 7 g, the drying rate suddenly drops to very low values and rapidly decays. This is because very little moisture is left in the potatoes at this point. When combined, the hybrid Microwave – Convection Drying process delivers a very typical exponential decay curve. The drying rate is not constant despite Microwave Radiation being used. This is because the use of hot air increases the rate of evaporation at the surface more than it increases the rate of migration of moisture from inner layers to the surface, as already observed in the first experiment. This is why the combined method has a faster rate of evaporation compared to the rate of moisture migration and the drying rate decays exponentially. When desiccant assistance is used, the drying rate is higher than all other experiments at any period of time besides the very end of the drying process. The drying rate also decays more rapidly compared to all other experiments. This is because desiccant material creates a high vapor pressure difference between the layer of air surrounding the surface and the surrounding air. But unlike convective or microwave drying, dehumidification does not increase the rate of moisture migration directly by conducting heat into the water content present in the inner layers of food product. So the drying rate is much more inconsistent and nonlinear compared to all other methods for the last experiment. However, the non-uniformity of drying rate is tolerable due to the high reduction in drying time which preserves quality and improves yield of the dehydration process.

Surface temperature. The surface temperature for all experiments rises at an exponential rate. In the beginning of the drying process, the convective temperature appears to be close to the starting temperature. As already discussed, this is because the surface of the food item is highly saturated with moisture in the beginning of the drying process. The water that is evaporated from the surface acts as a

phase change coolant which absorbs 2.2 kJ of heat for each gram of evaporation⁶¹. As the moisture content in the food item reduces and as the rate of evaporation reduces, the rate of cooling drops as well. Therefore, the surface temperature and the overall temperature of the food item rises over time. For Convective Drying at 60 °C, the temperature of the surface is 35.1 °C in the beginning of the drying process despite the hot air being blown over the slices being at 60 °C. The lower temperature of the surface is due to the presence of moisture, the surface temperature tends to approach Wet Bulb Temperature which for Experiment – 1 is 33.8 °C. However, since evaporative cooling is not 100% efficient and because heat from air quickly conducts into the surface, the temperature is higher than WBT. The surface temperature also appears to stagnate once it reaches close to 60 °C towards the end of the drying process. This is because as the surface temperature approaches 60 °C, the temperature gradient between the food surface and the hot air approaches zero. So, the surface cannot reach temperatures above the temperature of the hot air. For Microwave drying, the surface temperature sees a very sudden change in rate of temperature change. This may be explained by the surface drying out much faster than the inner layers, which is followed by the surface temperature elevating to very high levels as the rate of evaporative cooling is reduced. However, the experiment may have to be repeated for other food and textile items in different forms (powders, layers, bulk bodies etc) to validate whether this is indeed the reason for a sudden hike in temperature observed with Microwave drying. The combined Microwave – Convection drying process delivered a standard exponential growth, but the slope of the drying curve was found to be lower in the beginning of the drying process. This can be explained by the fact that the moisture removal rate at the surface for Microwave – Convection drying is higher than either Microwave or Convective drying individually. It follows that the rate of evaporative cooling does not significantly drop until the surface has been sufficiently depleted of water. Most interestingly, it was found that the slope of the temperature curve increases until the temperature reaches 60 °C but reduces beyond that point. This is because after the surface temperature exceeds 60 °C, the hot air acts to cool down the surface rather than heat it up. This is a highly beneficial feature of combining radiation and Convective Drying. At the time when the surface is most vulnerable to high temperatures i.e., towards the end of the drying process, the combined process attempts to keep the temperature from rising to very high values, unlike Microwave drying alone. Finally, for desiccant assisted Microwave – Convection drying, the starting temperature of the potato slices was found to be much lower than that obtained in other experiments. This follows from the fact that dehumidification reduces the WBT from 33.8 °C for other Convective Drying experiments down to 27.6 °C for Experiment – 4. The potato slices also reach the target 7 g weight before the temperature rises to 60 °C. Thus, the maximum temperature that the surface is exposed to is also reduced. It must be noted that due to hot air flowing at 60 °C above the slices, the rate of increase in surface temperature reduced after it exceeded 60 °C just like Experiment – 3. But it was found that when desiccant material was used to dehumidify air, the reduction in rate of temperature increase was not as significant as that obtained without it. This is because the desiccant material depletes the moisture present at the surface much faster, leaving lesser water for evaporative cooling towards the end of the drying process. Even though this is an undesirable consequence, the process is still overall beneficial due to the reduced drying time and surface temperature.

Moisture ratio. All of the experiments were able to reach the target moisture ratio of 3% w/w. However, if the target moisture ratio were higher, the difference in time taken to reach the target moisture ratio between different experiments would have been lower. This is because for each experiment, the drying rate slows down more and more as the moisture ratio reduces. Thus, if the goal is to dry the product to a higher moisture or if a lesser level of dehydration is required, the drying time is reduced for all experiments.

Color Retention. It was found that Convective Drying resulted in the lowest level of color retention. Most of the potato surface was darkened and browned by the end of the experiment. This is because the first experiment subjects the potato slices to high temperatures for the longest duration compared to rest of the experiments. Alongside scorching, the prolonged air flow increases Oxidation at the surface which results in browning. The high temperatures slowly burn the surface as it depletes its moisture and becomes more and more temperature sensitive. Microwave drying reaches much higher temperatures in comparison but preserves 11% more color than Convective Drying. This is because the duration for which the potato slices are exposed to high temperatures is significantly reduced when they are heated volumetrically. When the process is combined, Microwave-Convection preserves 71.6% of the original color, which is higher than either Microwave or Convective Drying individually. This is due to the reduced drying time and control over surface temperature. So, the surface is exposed to high temperatures for a much shorter duration. Moreover, forced convection keeps the temperature from elevating to very high values towards the end of the drying process. This prevents the surface from scorching when it is most vulnerable to high temperatures. Finally, when desiccant dehumidification was combined with Microwave-Convection, the product retained 87.8% of its color. This is comparable to the results obtained with Freeze drying while consuming only a fraction of the energy in comparison^{36,62-66}. This is because desiccant dehumidification lowers the WBT and keeps the potato surface at a much lower temperature throughout the drying process. By the time dehumidification becomes ineffective and the surface temperature starts reaching unsafe values, the target moisture ratio is achieved. The higher rate of evaporative cooling from the food item is the reason due to which the drying time and surface temperature are lower and therefore the product preserves a high percentage of its original color.

Conclusion

This study was conducted based on literature review which suggested that dropping overall drying time and surface temperature resulted in improvement of cosmetic quality of the product. It was also known that Convective Drying and desiccant dehumidification are processes that can be primarily powered by solar thermal collectors and therefore position themselves as environmentally and financially sustainable solutions for producers and manufacturers in developing regions. It was theorized that combining desiccant dehumidification with Microwave radiation and Convective Drying would result in the shortest drying time and highest color retention compared to the results obtained without it. The results were validated as the drying time was reduced by 13.3% by using desiccant dehumidification and the color retention was improved by 16.2% compared to the results obtained without desiccant dehumidification. It is therefore

concluded that using a single source solar thermal collector to power Convective Drying and desiccant regeneration and combining the process with Microwave radiation delivers high quality dried food snacks while reducing the Carbon emissions of the preservation process.

Declarations

Code availability

Image thresholding for measurement of color retention was done using Python language. The original code and images that were analyzed are attached as supplementary data. Further measured data can be requested from the corresponding author.

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Author contributions

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Competing interests

The authors declare no competing interests.

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Figures

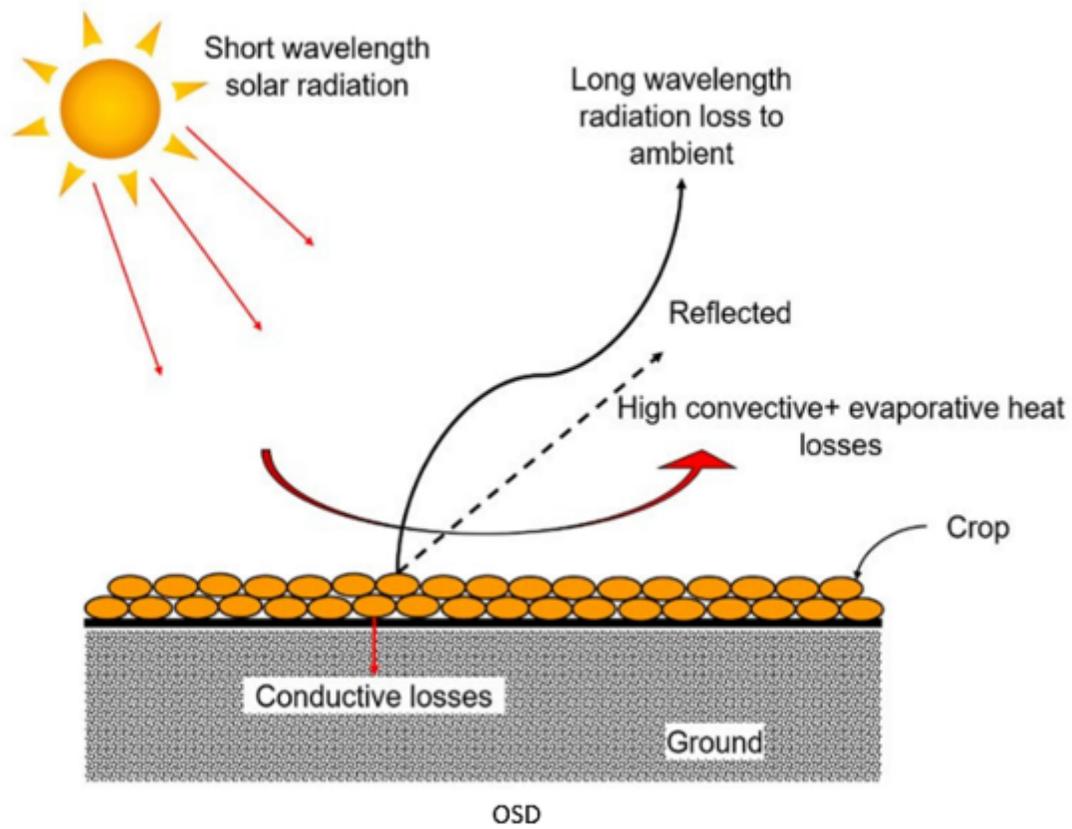


Figure 1

Drying phenomena of Open Sun Drying16

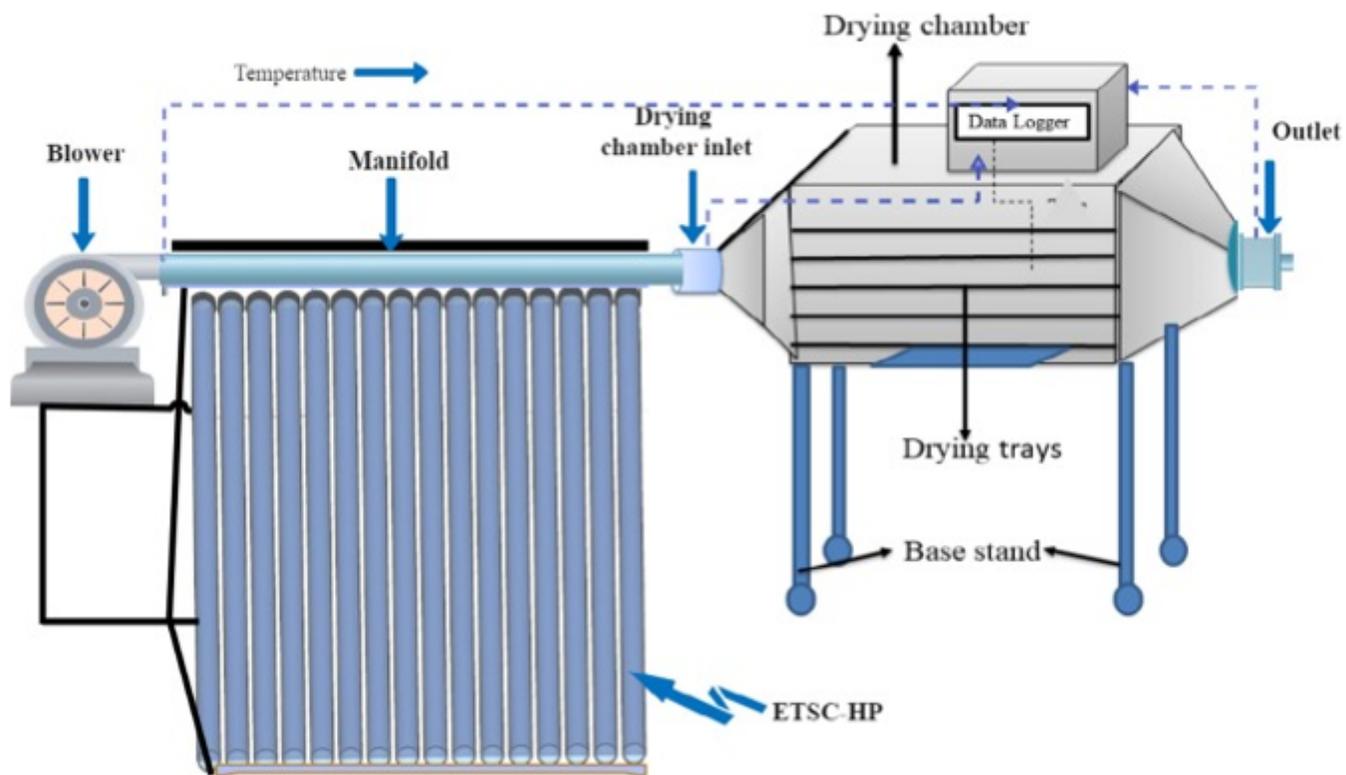


Figure 2

Solar Evacuated tube based forced convective drying67

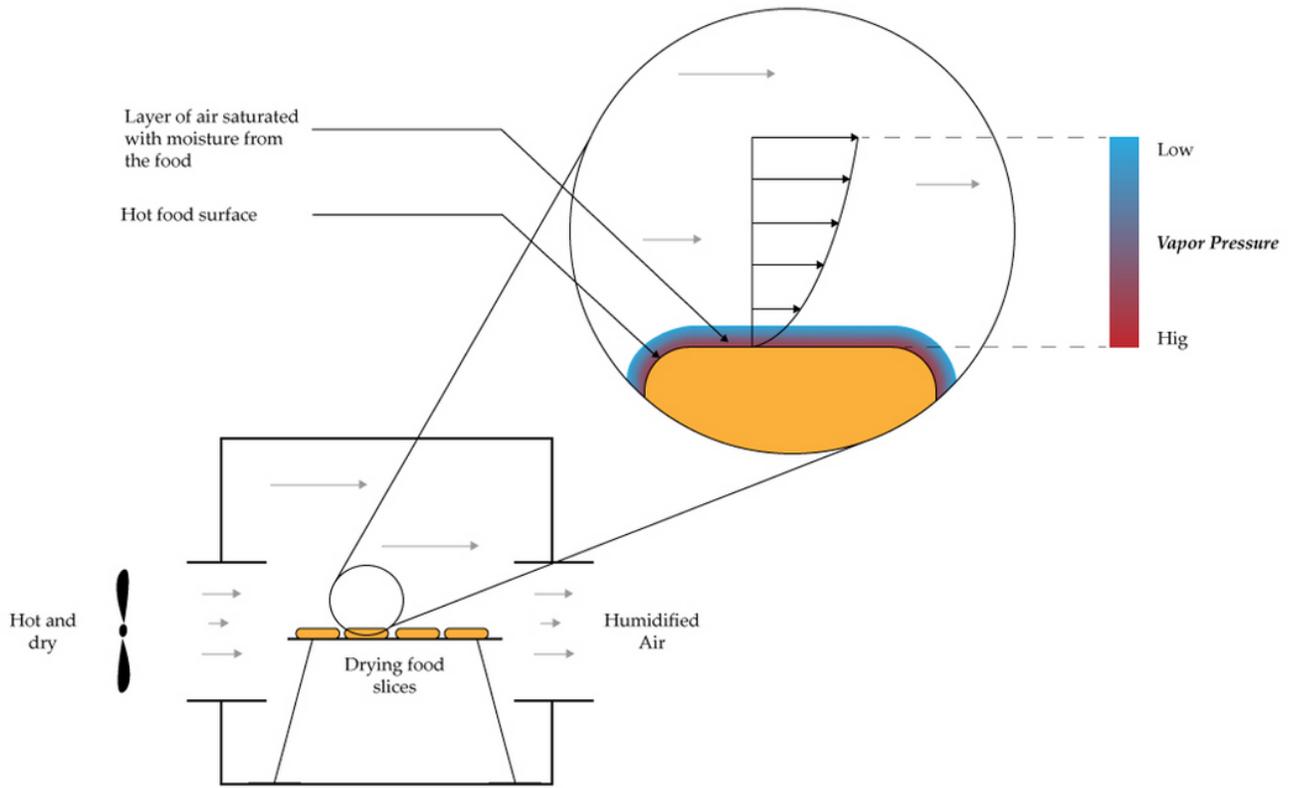


Figure 3

Schematic of Convective Drying food, depicting high moisture saturation and vapor pressure in air closest to the food surface

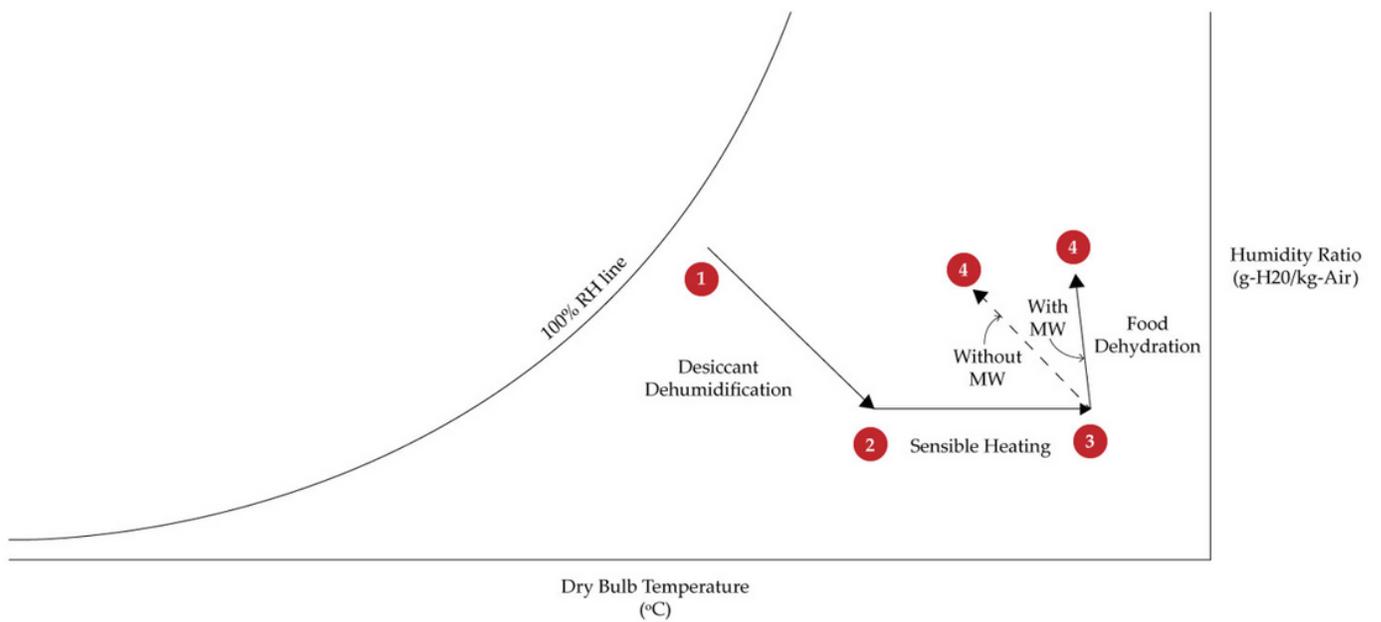


Figure 4

Desiccant dehumidification, followed by sensible heating, followed by hydration of air

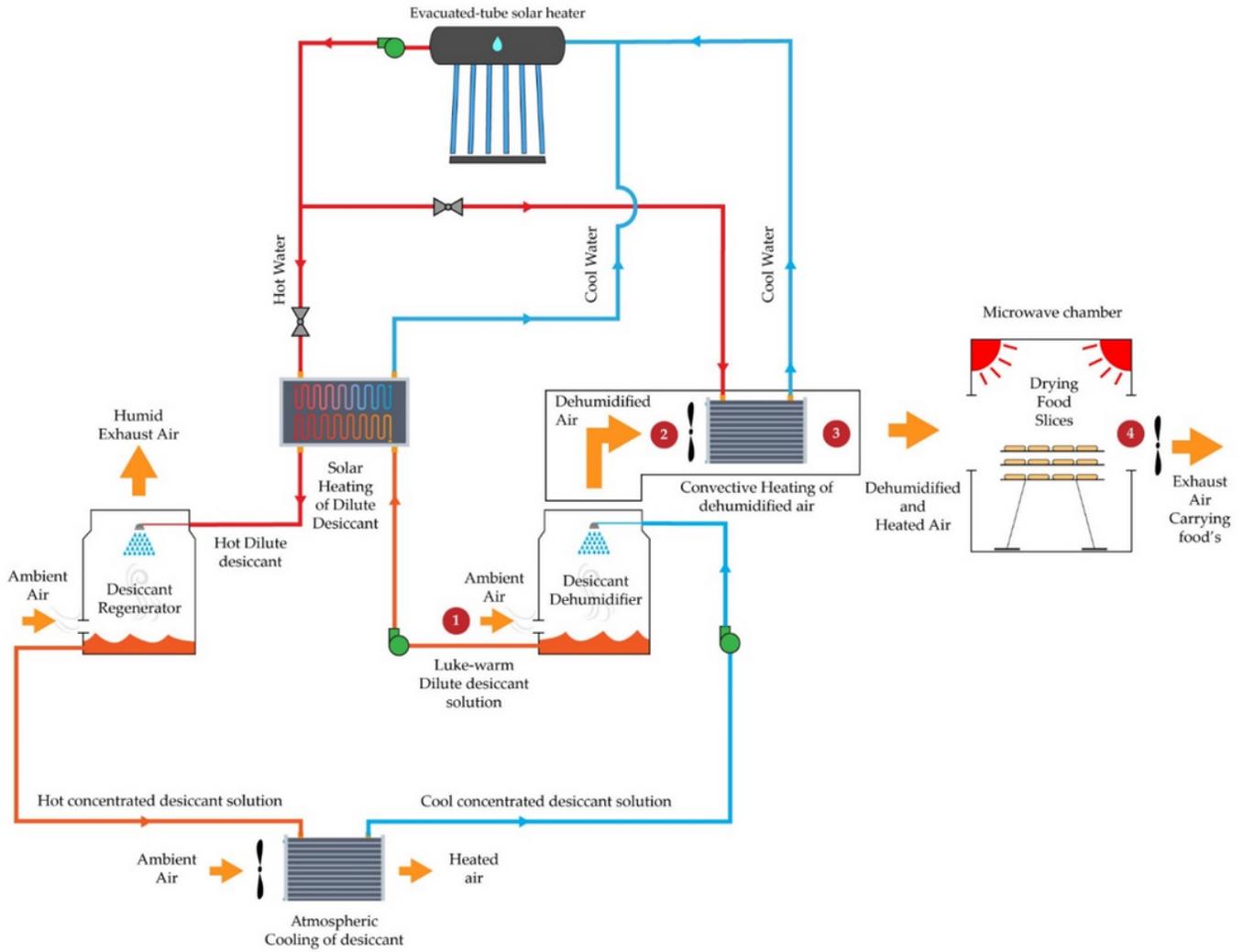


Figure 5

Schematic of the process developed to conduct solar regenerated desiccant dehumidification with convective and Microwave heating

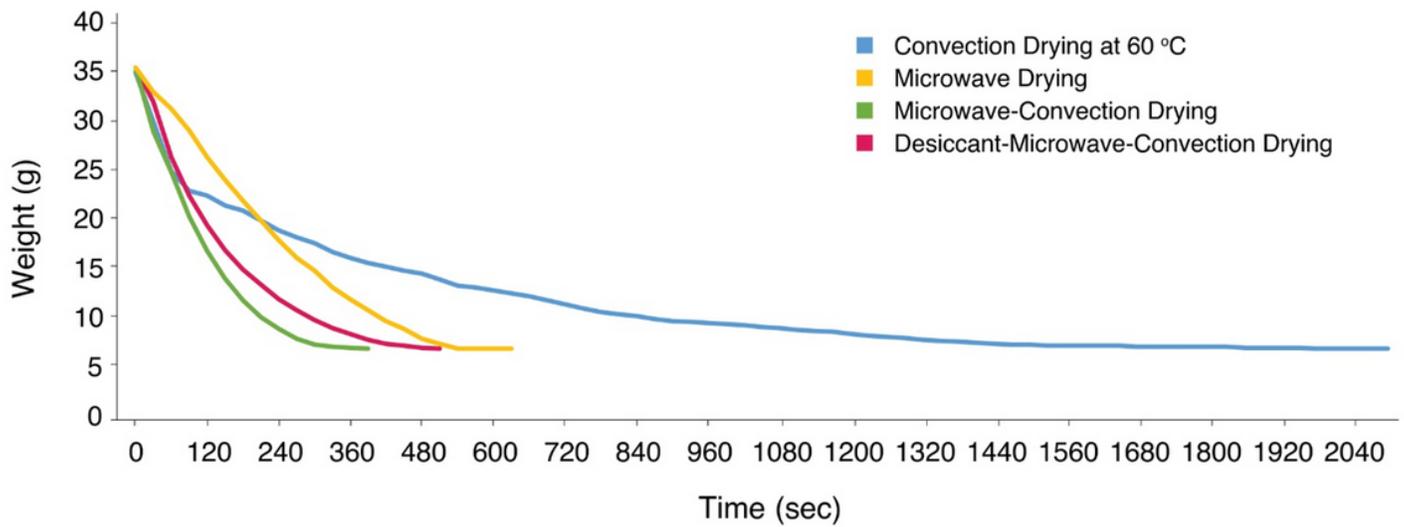


Figure 6

Mass of the potato slices graphed against the course of drying time

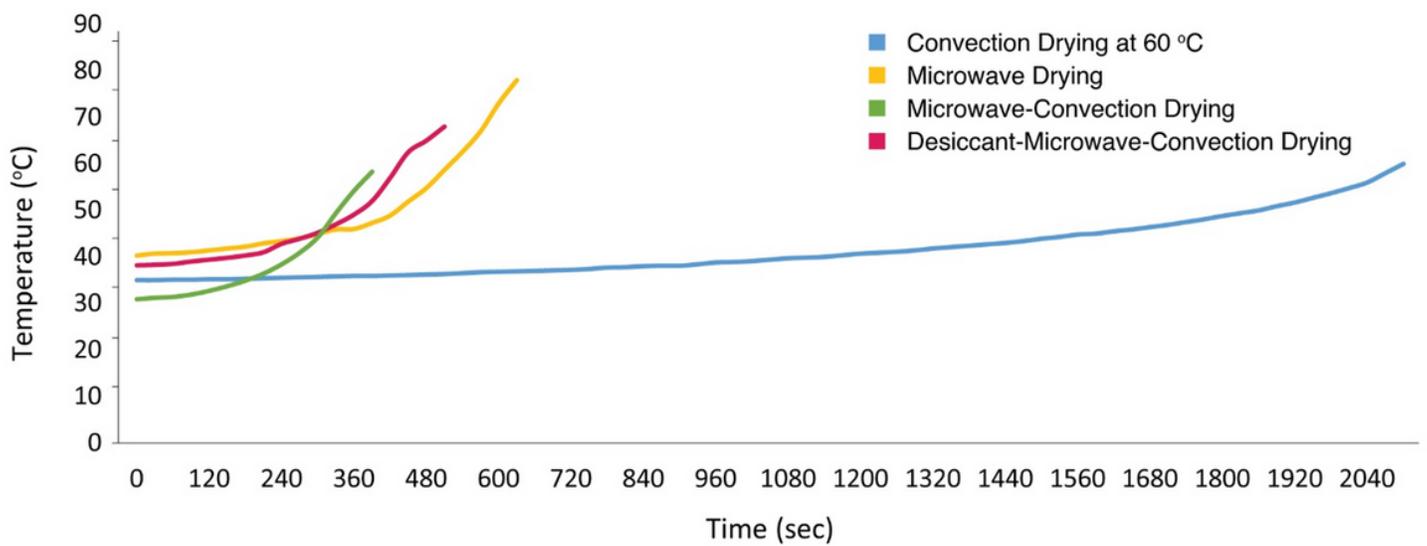


Figure 7

Surface temperature of the potato slices graphed against the course of drying time



Constant temperature Convective Drying at 60 °C



Microwave Drying



Microwave-Convection Drying at 60 °C



Desiccant assisted Microwave-Convection Drying at 60 °C

Figure 8

Before and after images of potato slices dried with different methods